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HIGH ALTITUDE PLASMA EFFECTS

B. Arnush, et al

TRW Systems Group

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The principal results of the TRW laboratory program to simulate ionospheric modification field experiments in the QUIPS device are reviewed. The main conclusions are:

1) By linear mode conversion, electromagnetic waves (EMW) produced very intense electron plasma waves propagating along the density gradient. There is no threshold for this process. 30

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In the ionosphere, this effect would produce waves which scatter VHF and UHF into sidebands displaced by the heater frequency (very sharp plasma lines) as from planes perpendicular to the density gradient in the interaction region.

2) The linearly converted EPW was the lowest threshold pump of the parametric instability. In the ionosphere the density gradient aligned linearly converted wave, as well as its decay products, provides a large field component perpendicular to the magnetic field and hence may drive an unstable perpendicular plasma mode and contribute to aspect-sensitive scattering.

3) In square wave operation the ponderomotive force produced a large pulse of density, proportional to incident power, which propagated away from the plane of reflection of the EMW.

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PUBLICATION REVIEW

This technical report has been reviewed and is approved.

RADC Project Engineer

RADC Contract Engineer

SUMMARY

The principal results of the TRW laboratory program to simulate ionospheric modification field experiments in the QUIPS device ~~(see the~~ Appendix) are reviewed. The main conclusions are:

1. By linear mode conversion electromagnetic waves (EMW) propagating in the inhomogeneous laboratory plasma produced very intense electron plasma waves (EPW) (orders of magnitude above the EMW) propagating along the density gradient. There is no threshold for this process (i.e., it occurs for an arbitrarily small pump).

In the ionosphere, this effect would produce waves which scatter VHF and UHF into sidebands displaced by the heater frequency (very sharp plasma lines) as from planes perpendicular to the density gradient in the interaction region. For a weak pump the density gradient is vertical and the planes are horizontal. For a sufficiently strong pump (whether Platteville exceeds that strength is unknown) striations may produce density gradients which are predominantly field-normal and hence give rise to a conventionally aspect-sensitive plasma line. This will also occur if the ionosphere is naturally striated along the field lines.

2. Unanticipated by conventional theory, the linearly converted EPW was the lowest threshold pump of the parametric instability. Similarly, in the ionosphere the density gradient aligned linearly converted wave, as well as its decay products, provide a large field component perpendicular to the magnetic field (proportional to the cosine of the dip angle) and hence may drive any of the several unstable perpendicular plasma modes and contribute to aspect-sensitive scattering.

3. In square wave operation, at the turn-off and turn-on of the EMW pump, the ponderomotive force due to the electrostatic field of the linearly converted EPW produced a large pulse of density perturbation, proportional to incident power (i.e., without threshold), which propagated away from the plane of reflection of the EMW.

1. MOTIVATION AND OBJECTIVES

In diagnostic field experiments, observations of high frequency ionospheric modification are necessarily limited to the measurement of a relatively small number of parameters in a relatively narrow segment of their relevant ranges. The most striking observations, namely those associated with field-aligned scattering, involve ionospheric structures which develop over a relatively long period of time (fractions of seconds or longer) and hence provide little information concerning the detailed mechanism responsible for the initiation of these structures. Thompson scattering provides information concerning the early time development but only at a single scattering frequency and with a narrow range of angles so that only a very limited portion of the wave spectrum which exists at altitude can be observed directly.

On theoretical grounds specific physical mechanisms, principally involving parametric instabilities, were proposed.[1] Since direct experimental verification of these hypotheses, for example, by in situ measurements, were not possible, laboratory plasma experiments were initiated to provide at least partial verification of the theoretical pictures. Simulation of the ionospheric phenomena in this way is feasible since many of the critical dimensionless parameters can be at least approximately reproduced in the laboratory. These include the ratios of density gradient length to wavelength (H/λ), cyclotron frequency to plasma frequency (ω_{ce}/ω_{pe}) and wavelength to Debye length (λ/λ_D); the wave damping (ν/ω); and the electromagnetic pump strength ($E^2/4\pi nkT$).

In general, the attempt to verify the theoretical picture has proved successful; even more significantly, the laboratory experiments have revealed the possible critical importance of phenomena not previously considered. Exploitation and application of these new ideas will require an appropriate field experiment to demonstrate that the effects involved occur in the ionospheric plasma as well as in the laboratory plasmas.

II. PROGRAM ORGANIZATION

When the laboratory program was implemented, the most satisfactory available plasma device appeared to be the "Q-machine," which has for the last decade served as a work-horse for laboratory plasma investigations. The plasma densities which can be achieved (10^7 to $10^{12} cm^{-3}$) correspond to a plasma frequency in a convenient microwave regime and the electron and ion temperatures are comparable, as is the case in the ionosphere. However, the necessity for a fairly strong magnetic field (5 to 10 kG) results in a value of ω_{ce}/ω_{pe} much larger than in the ionosphere and the relatively small radial dimensions (typically a few centimeters) preclude large values of H/λ. In addition, the electrostatic modes follow the Gould-Trivelpiece dispersion relation for a bounded plasma rather than the Bohm-Gross dispersion relation characteristic of the ionosphere. These considerations led to the initiation of a parallel effort, involving a much larger quiescent plasma which could operate in a smaller magnetic field. This was achieved by scaling up (by a factor of 30 in volume), a type of quiescent plasma device previously developed by Prof. Kenneth McKenzie of the University of California at Los Angeles. The details of this facility are described in the Appendix. We simple note here that in addition to permitting a correct ionospheric value of ω_{ce}/ω_{pe} and accommodating Bohm-Gross rather than Gould-Trivelpiece modes, it permits an H/λ of order of 10^2 and the matching of ionospheric values for the other parameters cited in Section I. (While this H/λ value simulates the ionosphere in the sense of being very large, it is still somewhat smaller than typical ionospheric values, a fact which must be kept in mind in comparing laboratory and ionospheric results.) In any case, large H/λ is essential in order to have electromagnetic pump waves rather than electrostatic excitation and to allow observations of linear mode conversion, convection of parametric decay waves and spatial development and localization effects, using suitable probes.

III. EXPERIMENTAL RESULTS

1. Electromagnetic Wave Propagation in Inhomogeneous Plasma. The predicted classical behavior has been verified, including the diminution in group velocity as the wave approaches the plasma wave resonance at $z = z_c$ [where z is the axial direction of the chamber and the wave frequency $\omega_o = \omega_p(z_c)$], and the complete cutoff of the incident wave beyond that point.[2] With steady state excitation, the expected standing wave pattern associated with wave reflection at the cutoff is observed (Fig. 1). We find that spreading of the incident wave due to refraction in the plasma more than compensates for the expected Airy function swelling. When the transmitter is pulsed on rapidly, temporal development of the propagation process can be followed in detail with no interference from reflection at the chamber walls.

2. Initial Parametric Instability Results. The excitation of the parametric decay instability is seen with modest pump power (1 to 10 W). The threshold is anomalously low, being 1 to 2 orders of magnitude less than predicted by theory. Of greater significance is the fact that the polarization of the decay waves is completely contrary to initial expectations. Since the electromagnetic pump propagates in the axial direction its electric field is radial. The consequent radial oscillations of the plasma electrons should then give rise to electrostatic decay waves[3,4] (the ion acoustic wave, $\omega_{ia} = kC_s$, and electron plasma, or Langmuir wave $\omega_L = \sqrt{\omega_{pe}^2 + k^2 C_e^2}$ having both wave vector and electric field in the radial direction. However, experimental observations show that both waves propagate in the axial direction. In fact, until this was discovered all attempts to see the low frequency ion acoustic wave were unsuccessful and only the Langmuir decay wave could be observed. The elucidation of this paradox ultimately led to a concept quite different from the commonly accepted ideas concerning the physical process involved in the Ivory Coral experiments, as explained below.

3. Linear Mode Conversion. The explanation of the axial decay wave polarizations described above was provided by the well known phenomenon of linear mode conversion.[5] Oblique incidence of the electromagnetic wave

results in an axial component of the electric field, i.e., a component parallel to the density gradient and hence to an oscillating charge separation which tends to become very large at the resonant point, $\omega_o = \omega_p$. The associated self-consistent short wavelength axial electrostatic field will be limited in amplitude [by either thermal effects (finite Debye length) or collisional effects] but in both the ionospheric plasma and in QUIPS it can attain a value very much larger than that of the incident electromagnetic wave. Hence, this linearly converted electrostatic wave, rather than the incident electromagnetic wave, will serve as the pump for the parametric instability.

Detailed experimental observations[6] of the amplitude and shape of the short wavelength structure in the electric field at the resonance point support this picture (Fig. 2). Theory predicts a shape given by one of the inhomogeneous Airy functions[7] and the experimental agreement is excellent. Direct measurement of the amplitude of the linearly converted mode has proved very difficult because physical probes sharply reduce it, but a very rapid turn-on of the pump (within a few nanoseconds) produces perturbations of plasma density in the resonant region, caused by the ponderomotive force $\langle \nabla E^2/8\pi \rangle$. Since the measured amplitude of the electromagnetic pump is too small by two orders of magnitude to produce the observed density perturbations ($\delta n/n \approx 1$-5%), we have concluded that the ponderomotive force associated with the linearly converted mode must be responsible. Indeed, the theoretically predicted amplitude for this mode is consistent with that required to produce the observed density perturbations.

4. <u>Detailed Study of Parametric Instabilities</u>. Both the Langmuir and ion acoustic decay waves have been observed propagating in the axial direction[8] as is expected[9] for the axial electrostatic pump arising from linear mode conversion (Fig. 3). A clear threshold can be detected, above which there is frequency broadening as predicted by theory. Pulsing the pump allows observation of the time evolution of the parametric decay process (Fig. 4).

5. <u>Density Modifications Due to the Ponderomotive Force</u>. In view of the large electrostatic field produced by linear mode conversion as discussed above, density perturbations proportional to incident power would be expected and are indeed found (Fig. 5). Careful measurements with pulsed pump signals

and detailed Langmuir probe observations show that the observed signals are indeed due to changes in density rather than electron temperature or ionization, and the density perturbations are observed to propagate with a speed approximately equal to the ion acoustic velocity c_s as expected. Under steady state excitation the peak of the linearly mode converted electrostatic field coincides with the local (relative) minimum of plasma density. No threshold for these effects is expected or observed, beyond that set by diagnostic limitations; these correspond to power levels of a few watts.

6. Effect of an External Magnetic Field. Addition of a 200 gauss magnetic field approximately reproduces the ionospheric value of ω_{ce}/ω_{pe}. While further work remains to be done, we have found that addition of the magnetic field does not alter the linear mode conversion phenomena or the associated generation of a density perturbation significantly. However, these perturbations propagate somewhat slower across the magnetic field than in the field-free case.

7. Double Resonance Phenomena. The use of two pump frequencies separated by a suitably chosen low frequency, ω_l, in the ion acoustic regime has been explored in the QUIPS with a view towards devising suitable ionospheric field experiments.[10] If the separation frequency, ω_l, is chosen to equal the frequency of the ion acoustic waves which occur for single pump parametric instability, the threshold for that instability is greatly reduced. Other choices for ω_l provide the freedom to select the low frequency generated in the plasma (Fig. 6)

8. Scattering of 8mm Waves. This system is now operational and several experiments have been carried out. With double resonance excitation, observation of the ion acoustic component has been successful but efforts to unambiguously detect the Langmuir sideband have encountered difficulties associated with spurious mixing of the 8mm and pump signals (Fig. 7).

III. IONOSPHERIC IMPLICATIONS OF LABORATORY OBSERVATIONS

Theoretical arguments,[2,9] now bolstered by the QUIPS experiments in a magnetic field reported here, indicate that linear conversion will also occur in the ionosphere. The resulting electrostatic waves will propagate at a very small angle to the local density gradient (assumed, for the moment, to be predominantly vertical). They would therefore scatter RF waves as from a horizontal mirror in the disturbed region, consequently producing a north-south scatter link. Estimates of the cross section suggest that it varies as the square of the scattering frequency up to perhaps as much as 1 GHz vertically, and a correspondingly higher frequency at other angles, and that it may be quite large. Of course, since this effect is linear, it has no threshold and hence its observation is limited only by the sensitivity of the scattering link. Thus, if the cross section is sufficiently large, a question which can only be resolved by performing field experiments, scattering from these waves may be observed at reduced pump powers.

Vertically propagating linearly converted waves provide a large field component perpendicular to the magnetic field and hence may drive any of the several unstable perpendicular plasma modes and contribute to aspect sensitive scattering. Similarly, the ponderomotive forces these waves produce, which in turn produce large density perturbations in the laboratory may contribute significantly to the field-aligned density perturbations observed in the ionosphere.

If the short wavelength spectral components of a field-aligned density fluctuations, n_1, are sufficiently large (i.e., $H|\nabla n_1|/n_o >> 1$) then the density gradient will be predominantly perpendicular to the magnetic field and the linearly converted waves will propagate in the perpendicular direction. This may produce a very sharp field normal VHF and UHF sideband displaced by the heater frequency. Field-aligned density fluctuations can occur naturally, or may be produced by the pump.

IV. FURTHER RESEARCH

Further field experimental and theoretical investigations of the consequences of linear mode conversion appear warranted. In addition, the following appear to be potentially fruitful areas of future laboratory research:

1. Ponderomotive Force Effects in Magnetic Field

In addition to potentially shedding light on the formation of large magnetic field-aligned density fluctuations, ponderomotive force studies may also lead to the discovery of hitherto unanticipated effects such as beam plasma instabilities and wave or particle trapping.

2. Bernstein Modes

The threshold for parametric decay into Bernstein waves is theoretically[11] within the capacity of the Boulder antenna. These waves would be short enough to scatter S- and C-band radar waves.

3. Variable Ion Damping

By the introduction of a small amount of He in the QUIPS, the ion damping can be varied to better simulate the strong ion damping due to $T_e = T_i$ in the ionosphere. In addition to changing thresholds this can significantly alter thermal transport effects.

4. Thermal Effects

It has been suggested that a new thermal instability,[12,13] may be responsible for large scale field-aligned irregularities. The hypothesized interactions have never been explored in the laboratory.

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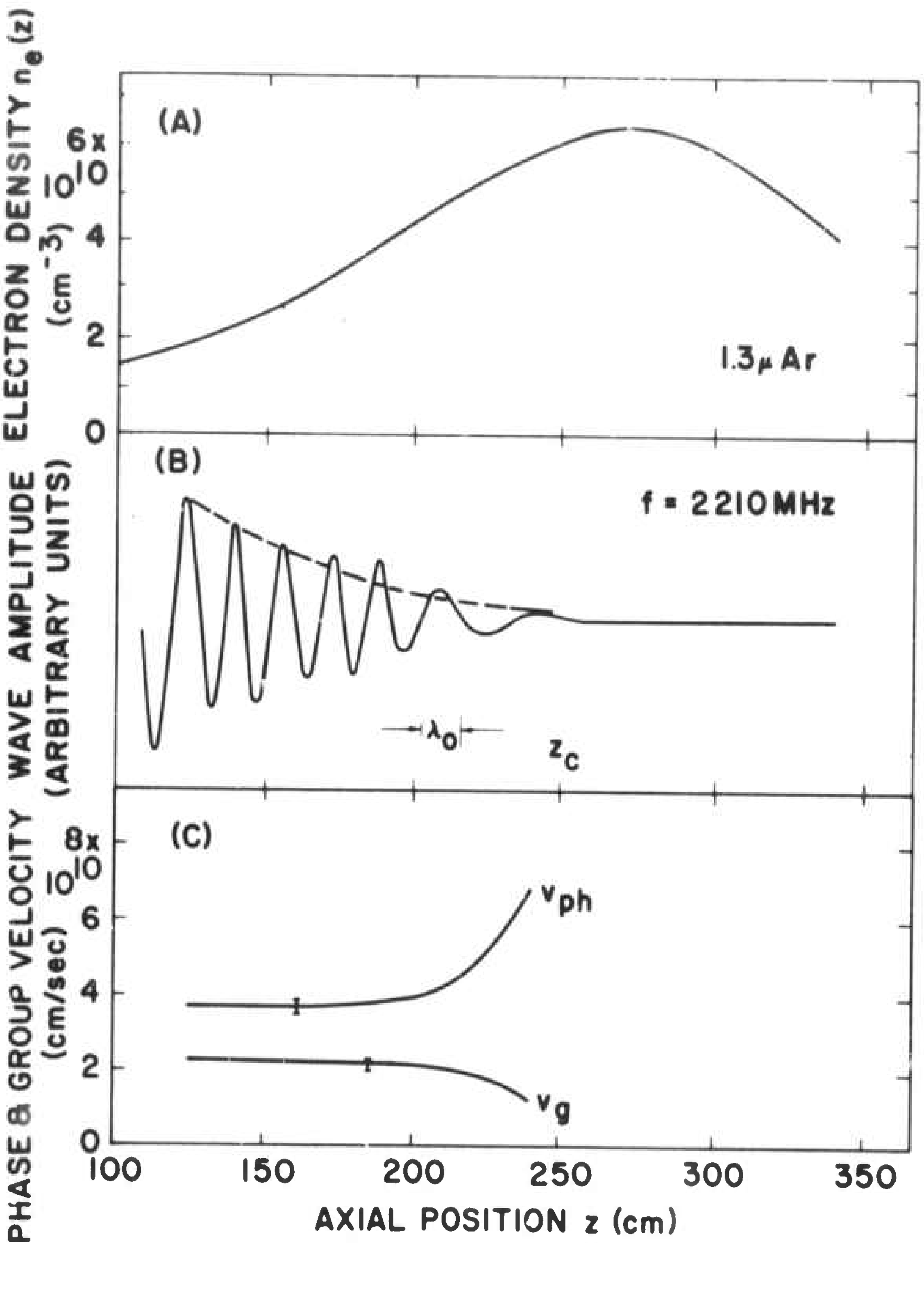


Figure 1. (A) Axial density profile; (B) Pump electric field vs. axial position sampled at a fixed time, t_1, $[E_{o(z)}\cos(\omega t_1 - kz)]$; (C) Behavior of phase and group velocity.

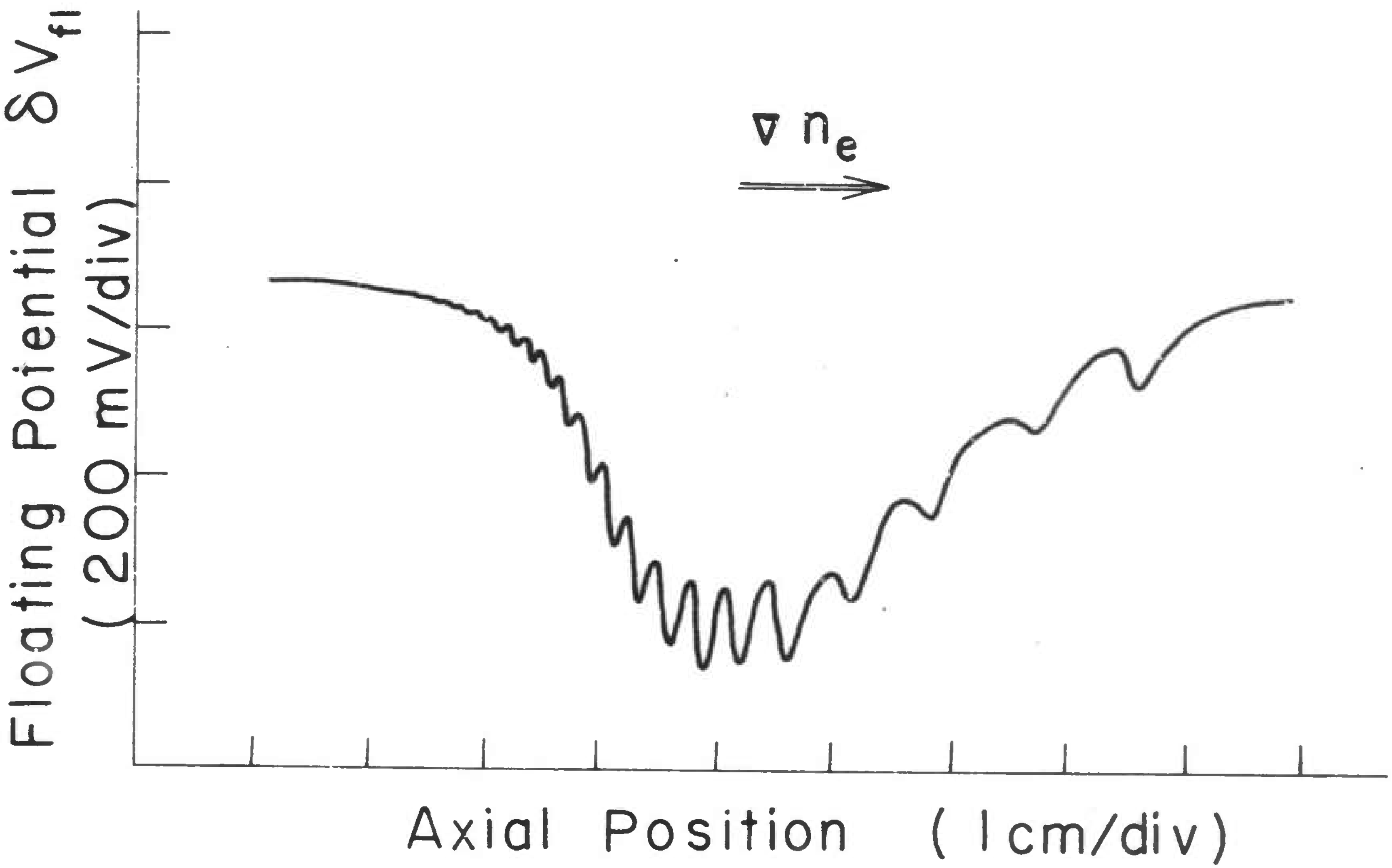
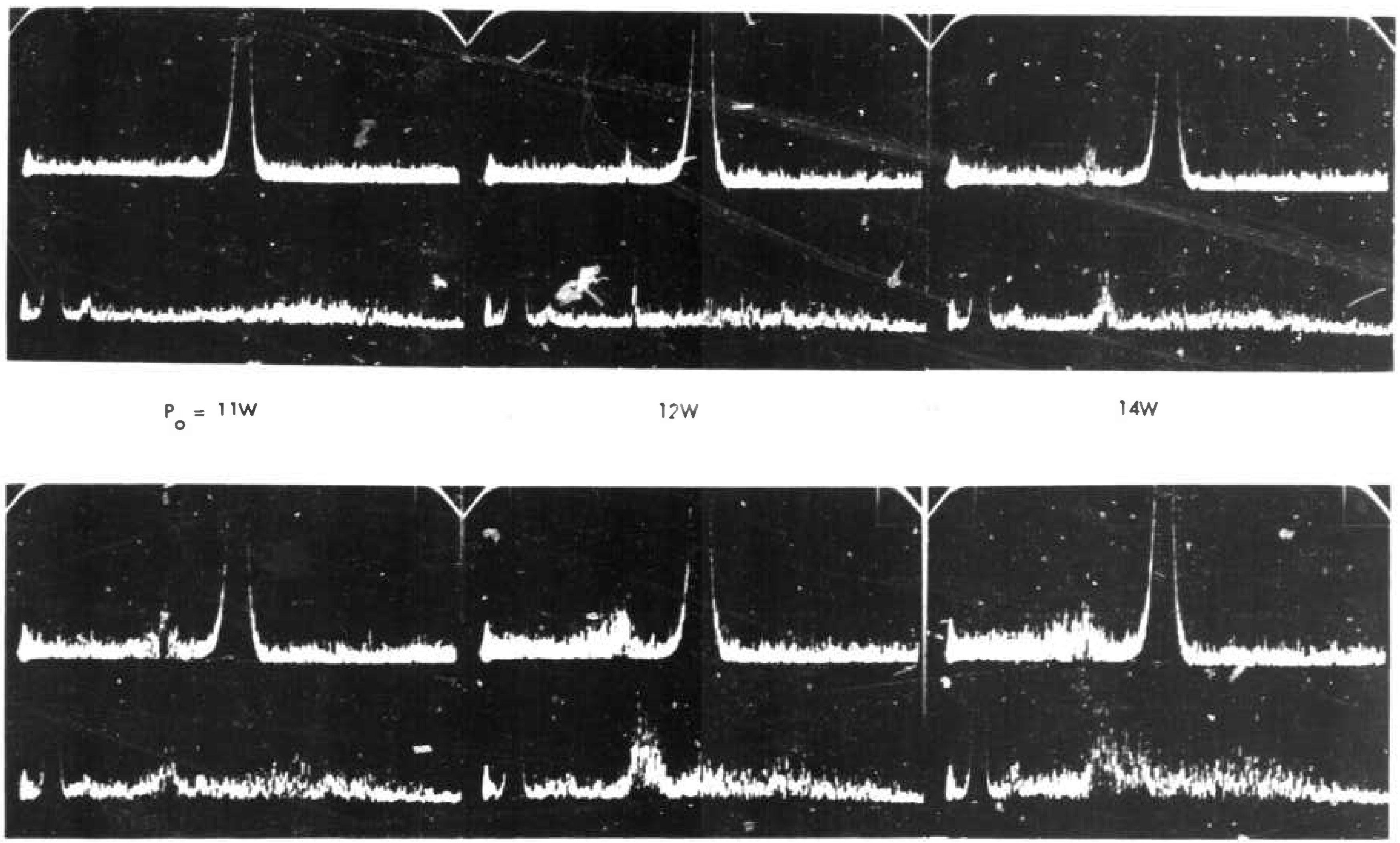


Figure 2. Change in floating potential due to rectification of electron plasma wave signal on probe sheath.



P_o = 11W 12W 14W

16W 18W 20W

Figure 3. Simultaneous frequency spectra of probe signals at different pump power levels, P_o.
<u>Top traces</u>: High frequency spectrum showing pump line and unstable electron plasma waves below the pump 300 kHz/div.
<u>Bottom traces</u>: Low frequency spectrum with zero-beat line and unstable ion acoustic waves.

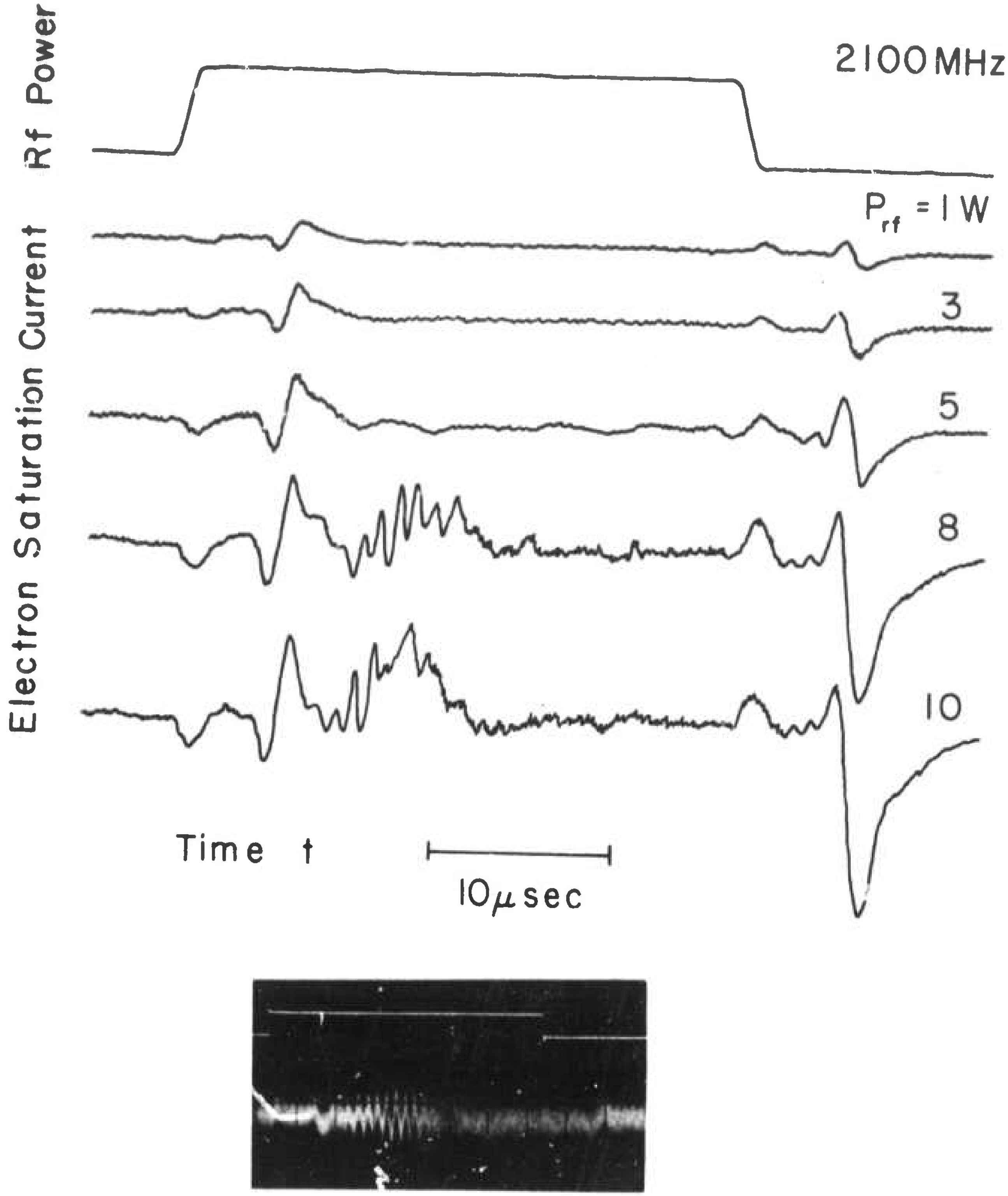


Figure 4. Time evolution of parametric ion oscillations and density perturbation by ponderomotive force.
<u>Top trace</u>: RF pulse
<u>Middle traces</u>: Electron saturation current vs. time at different pump power levels, P_{rf}. Note onset of oscillations above a threshold of $P_{rf} \simeq 6$W. The unstable ion oscillations are initially coherent, then develop turbulence.
<u>Bottom trace</u>: Polaroid picture showing turbulent ion oscillation level in comparison with coherent oscillations.
Large delayed transients are density perturbation by ponderomotive force.

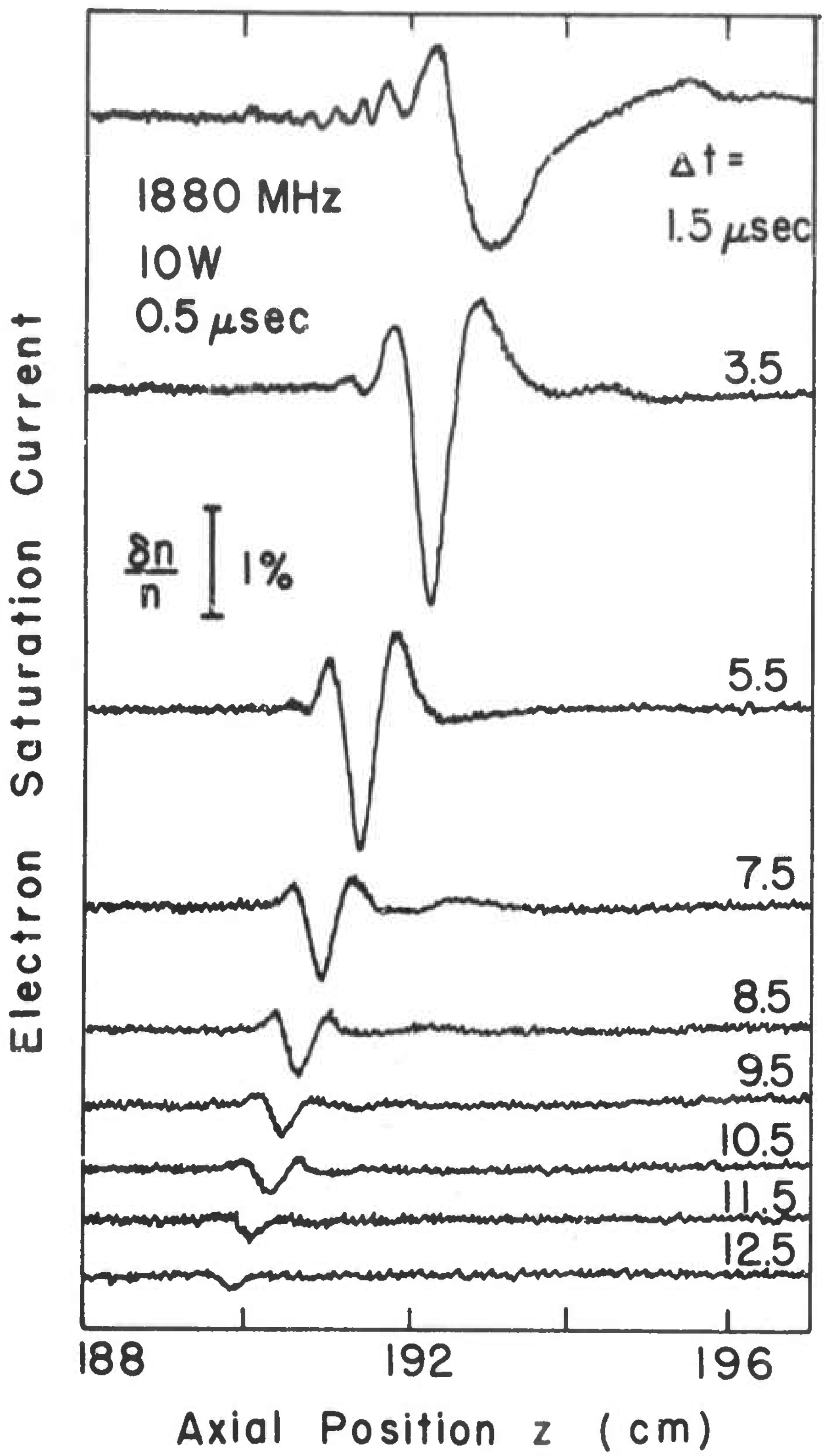


Figure 5. Density perturbation at time Δt after turn-off of microwave pulse. The ponderomotive force expels the plasma out of the resonant region.

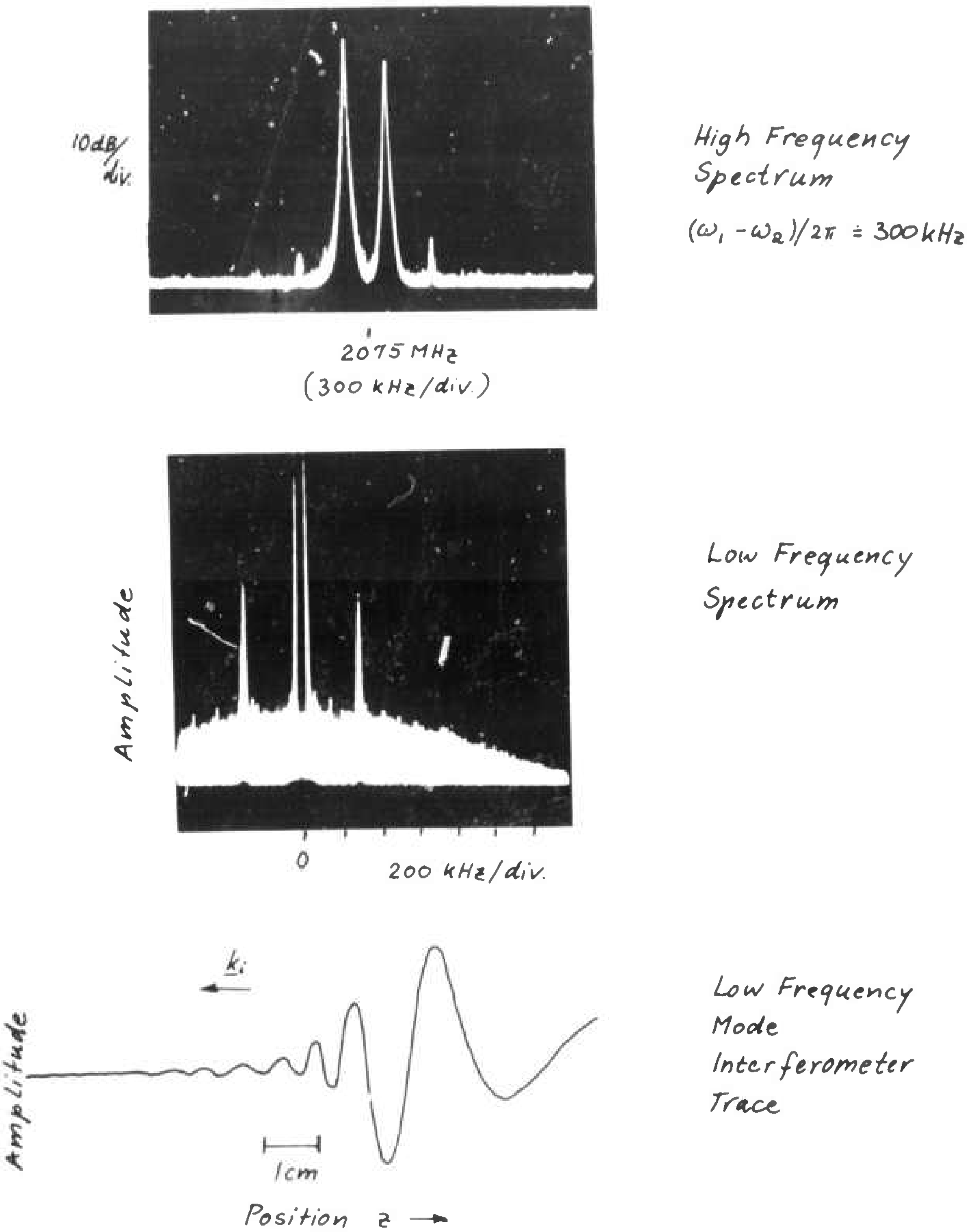


Figure 6. Double pump ion oscillations.

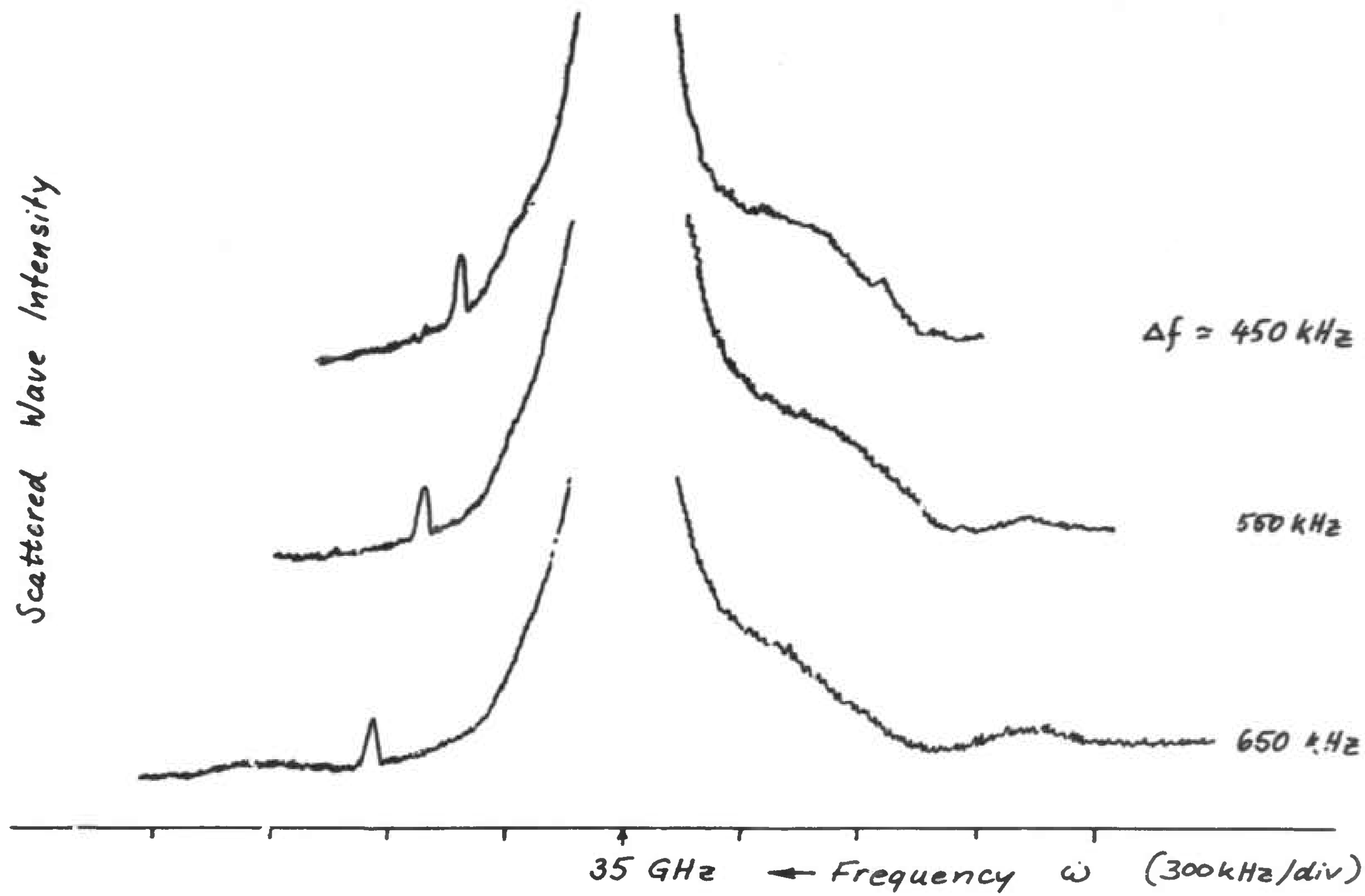


Figure 7. 35 GHz Thompson scattering spectrum. The upper line corresponds to ion oscillations created by double pump excitation, propagating toward the observer. The main center line results from reflections of the incident Thompson signal from the chamber walls.

APPENDIX

QUIPS

Quiescent Uniform Ionized Plasma System

For modeling F-layer phenomena the QUIPS design had the following major objectives:

(a) In order that the microwave pump (analog of, for example, the Platteville, Colorado HF transmitter) pattern be sufficiently simple, the wavelength, λ_o, of the pump must be much smaller than the size of the device (length $\ell \simeq 30\ \lambda_o$).

(b) In order to restrict the variety of plasma gradient scale length (L) dependent interacts to those which are likely to occur in the ionosphere the plasma must be sufficiently uniform ($L >> \lambda_o$).

(c) For a given plasma frequency, ω_{pe}, we must be capable of achieving magnetic fields and corresponding electron cyclotron frequencies, ω_{ce}, such that $\omega_{ce}/\omega_{pe} \cong 1/4$.

(d) Plasma noise must be sufficiently low to clearly detect the parametrically generated waves.

(e) Ion acoustic wave damping should be variable ($\gamma/\omega \cong 1$ since $T_e/T_i \cong 1$).

These conditions are partly mutually contradictory. For example, condition (a) is most easily achieved by maximizing the plasma density whereas condition (c) is most readily achieved by minimizing the plasma density. The resulting design is therefore a compromise among these, and various other practical considerations.

The useful plasma region is 172 cm in diameter and 365 cm in length (see Figure 1). Plasma is produced by a dc discharge in argon at about 1μ pressure. Up to twelve rings of tungsten filaments, biased about -40 volts with respect to the chamber wall, act as cathode and the chamber wall as anode. The chamber is lined with 10,000 permanent magnets to reduce the plasma losses. Usually two filament rings located near one end of the chamber are used to produce the desired axial density gradient. Electromagnetic waves are launched from a dipole at the focus of the parabolic antenna (radius 40 cm(and propagated into the density gradient along the axis of the device. Plasma diagnostics and wave diagnostics are performed with two radial probes and one axial probe, all movable with automatic probe-drive systems. With the racial probes we investigate wave propagation parallel to the electric field of the EMW.

The shaft of the radial probe is parallel to the EMW electric field, which perturbs the electromagnetic field pattern as the probe moves. The axial probe is in this respect better arranged because it has a minimum scattering cross section for electromagnetic waves, the shaft being perpendicular to the pump electric field. Three different types of probes are employed: 1) A magnetic loop antenna which picks up only the electromagnetic waves; 2) a shielded triple grid which launches and detects ESW; and 3) various coaxial Langmuir probes which are used to determine basic plasma parameters and to detect ESW and EPW. In addition, an 8 mm diagnostic scattering arrangement is used to probe the plasma without disturbing it and to more directly model ionospheric Thomson scattering experiments.

The basic plasma parameters are summarized in Table I. At high pressures for F-layer modeling, typically 1.3 microns of argon, we obtain plasma densities around $5 \times 10^{10} cm^{-3}$ which corresponds to a plasma frequency of about 2000 megacycles. The electron temperature is about 1.6 electron volts. The low frequency noise, when measured from the electron saturation current fluctuations, and integrated over the entire range of ion acoustic waves up to the ion plasma frequency, corresponds to a $\delta n/n$ of about 1%. There is high frequency noise around the electron plasma frequency with bandwidth of about 200 megahertz , presumably due to beam plasma instabilities caused by the fast primary electrons from the filaments. For the above parameters the density gradient scale length is about 100 centimeters in the axial direction, while the density is much more uniform in the radial direction with a scale length of about 500 cm or longer. Density gradient scale lengths much greater than the machine size are achievable in both directions but have not thus far been used for ionospheric modification modeling. At low pressures the plasma properties change drastically. While the primary electron density stays constant for a given discharge voltage and current, the plasma density decreases because the neutral density decreases. This can be seen on the Langmuir traces in Fig. 2. The upper Langmuir probe trace is taken at high pressures. The plasma potential and floating potential are properly separated by a few κT_e. In the lower trace the pressure has been lowered by three orders of magnitude. The electron density drops significantly (note the change in the current scale), and the primary electrons become easily visible. Taking the second derivative of the Langmuir probe trace yields the electron speed distribution function. One can see a large hump of electrons around -50 volts (the primary electrons) and a second hump near the plasma potential (the plasma electrons with T_e of about 4 electron volts). At low pressures the relative concentration of hot electrons to cold electrons can become as high as 10%. At high pressures ($P \sim 1$ micron) where parametric effects are being investigated, the primary electrons have little importance since their relative concentration has dropped to about 0.1%. The primary electrons simulate photoelectrons in the ionosphere. Although $T_e/T_i >> 1$ we can heavily damp ion acoustic waves by adding a small percentage of light ion impurities (He) to the heavy ion plasma (Ar).

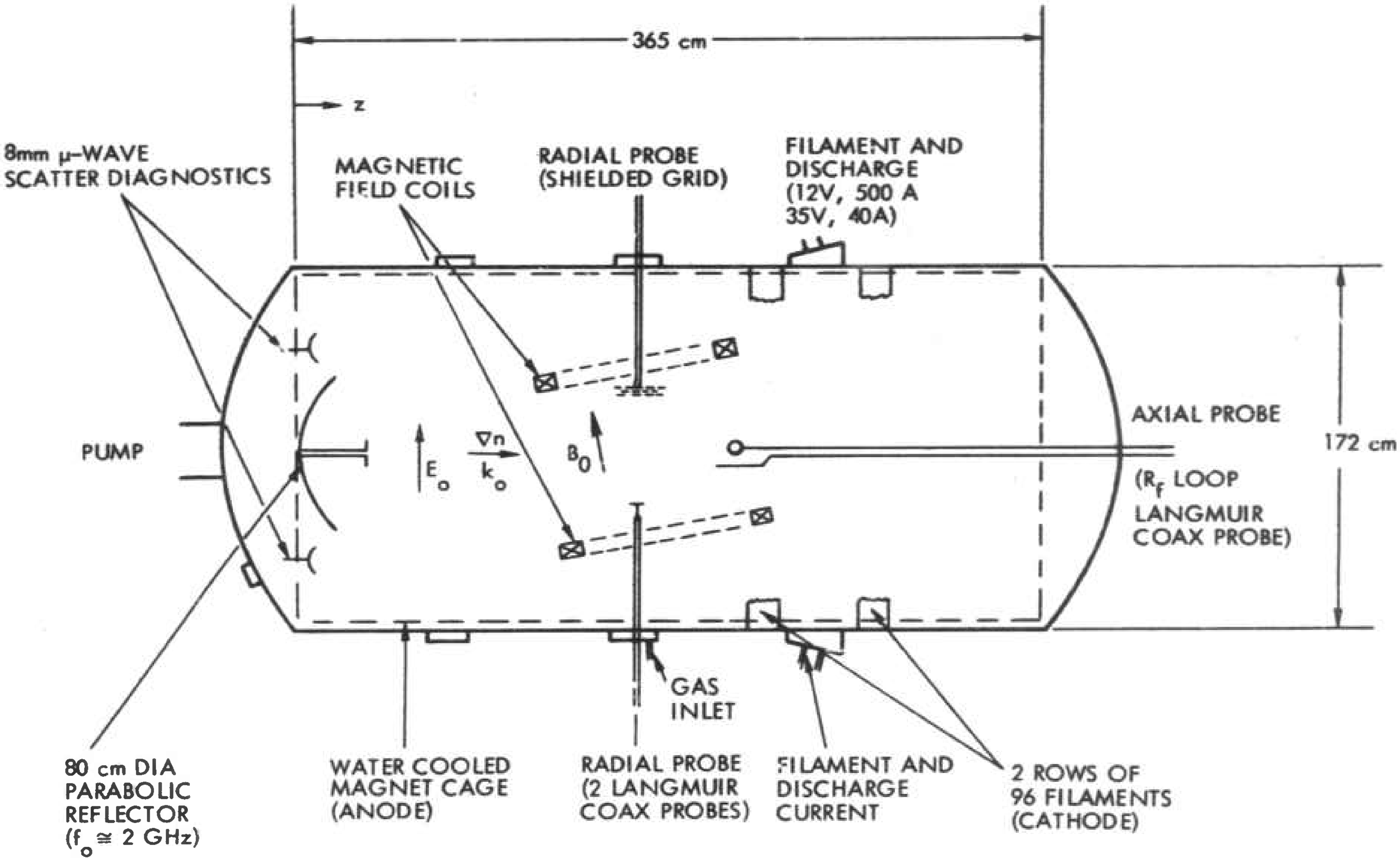


Figure 1 - Schematic of QUIPS showing the movable probes which contain Langmuir, RF and plasma wave sensors; the 80 cm diameter 15 cm microwave pump antenna; and two microwave diagnostic antennas. The magnetic field in the interior of the plasma can be varied from 0 up to the full field (several hundred gauss) of the Helmholtz coils, and its orientation relative to the propagation direction can be varied by rotating the coils.

Table I - Typical Operating Characteristics

BASIC PLASMA PARAMETERS

(@ 1.3μ Argon, $I_d = 41A$, $V_d = 35V$)

Density	$n_e = 5.2 \times 10^{10}\ cm^{-3}$
Temperature	$kT_e = 1.6\ eV$
Low Frequency Noise	$\delta n_e/n_e \gtrsim 1\%\ (0 < f < f_{pi} \simeq 7MHz)$
High Frequency Noise	$f \gtrsim f_{pe}\ ,\ \Delta f \simeq 200\ MHz$
Gradient Scale Length	$n/\nabla_z n \simeq 100\ cm$ $n/\nabla_r n > 500\ cm$
Ambipolar Electric Field	$E_z \simeq 16\ mV/cm$

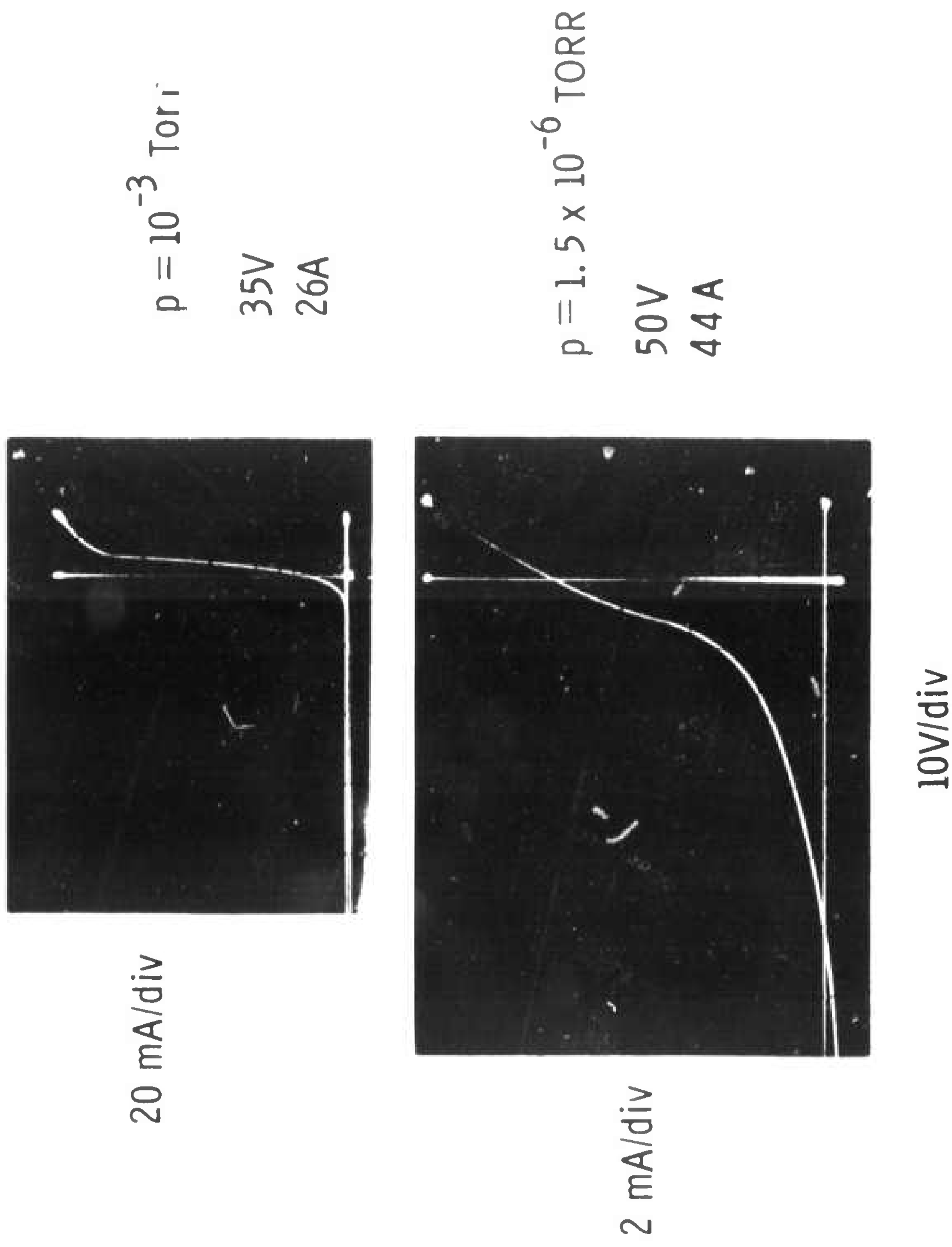


Figure 2. Langmuir probe traces at high and low pressures.

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